Progress in the development of a 5x5 array of Quantum Capacitance Detectors for far-infrared radiation

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Electron Beam Lithography by
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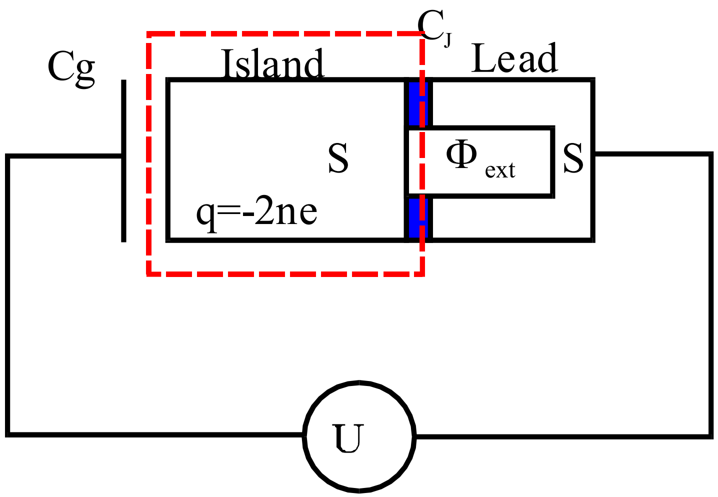
Single Cooper-Pair Box



Electrostatic gate charge $$n_G = \frac{C_G V_G}{2e}$$

Charging energy $$E_C = \frac{e^2}{2C_\Sigma}$$

Josephson coupling $$E_J = E_J^{\max}\left|\cos\left(\frac{\pi\Phi}{\Phi_O}\right)\right|$$

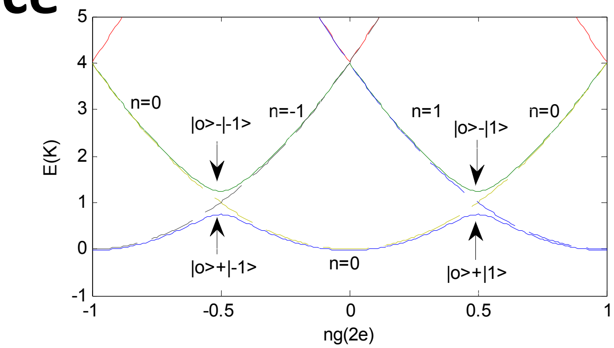
$$H = 4E_C \sum_n (n - n_G)^2 |n\rangle\langle n| - \frac{E_J}{2}\sum_n \left(|n+1\rangle\langle n| + |n\rangle\langle n+1|\right)$$

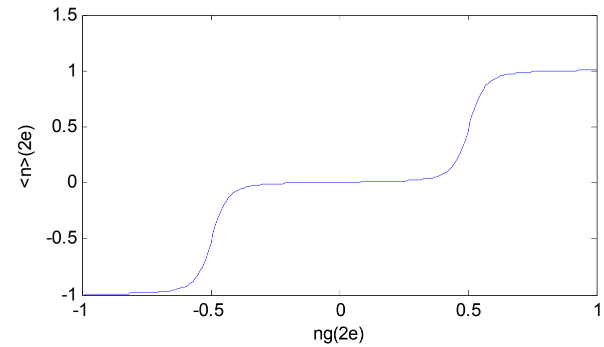
Energy levels, Coulomb Staircase and Quantum Capacitance

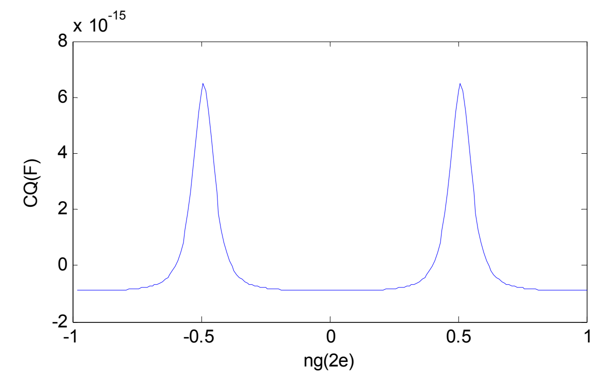
- In the absence of Josephson coupling, Energy is given by parabolas centered at integer values of Cooper Pair Charge

$$E = (Q - 2ne)^2 = (C_g V_g - 2ne)^2$$

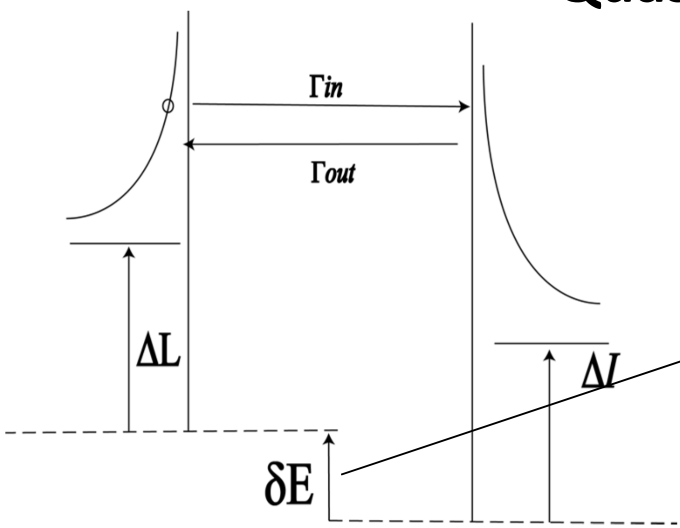
- As the gate voltage is increased, Cooper Pairs tunnel to minimize the energy and the charge on the island changes in a stepwise fashion
- The capacitance of the island $C_Q = 2e \dfrac{d\langle n \rangle}{dV_g}$ has peaks at the degeneracy points where the charge in the island is changing fast
- The Josephson Coupling introduces splittings in the energy levels
- Eigenvectors are symmetrical and anti-symmetrical combinations of the charge states
- The larger Ej, the "rounder" the charge staircase and the smaller the capacitance peaks
- In the absence of tunneling, only one parabola would exist (n=0) and the capacitance would be constant as a function of the gate voltage
- The variable capacitance is due to the quantum nature of the system and is called the quantum capacitance

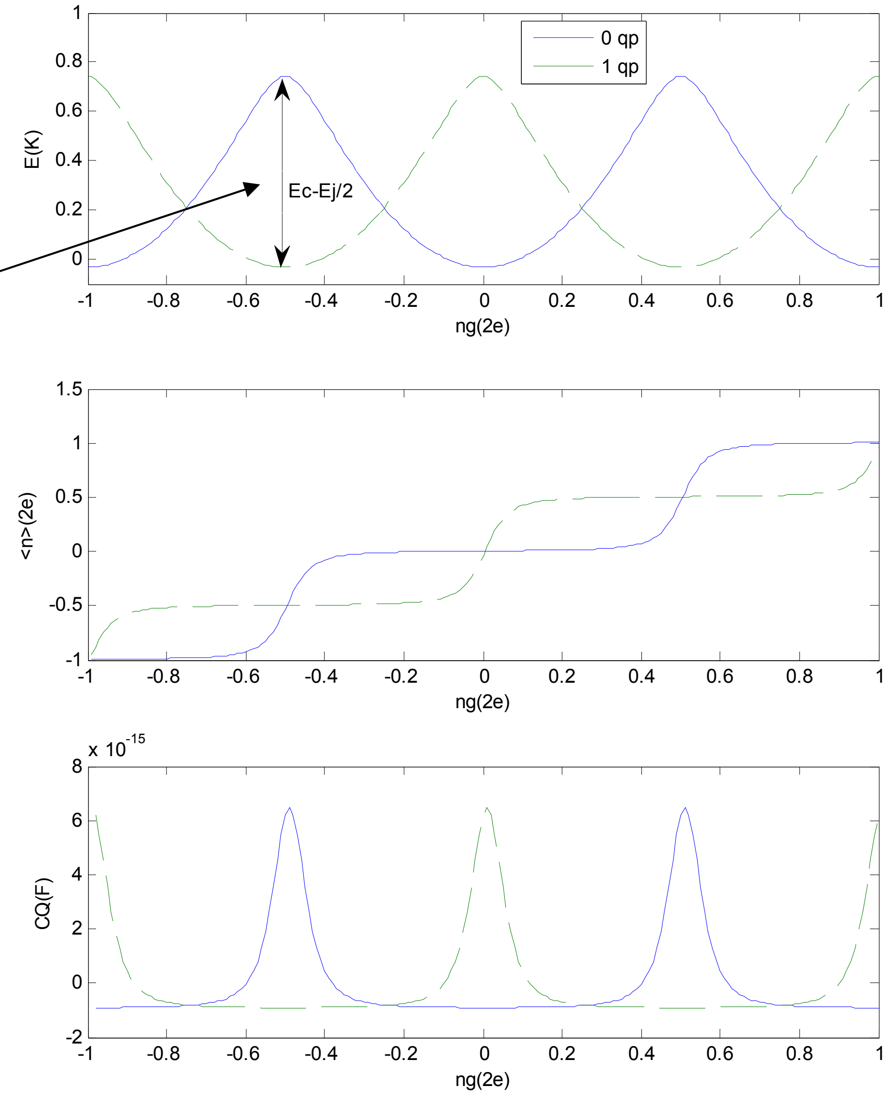






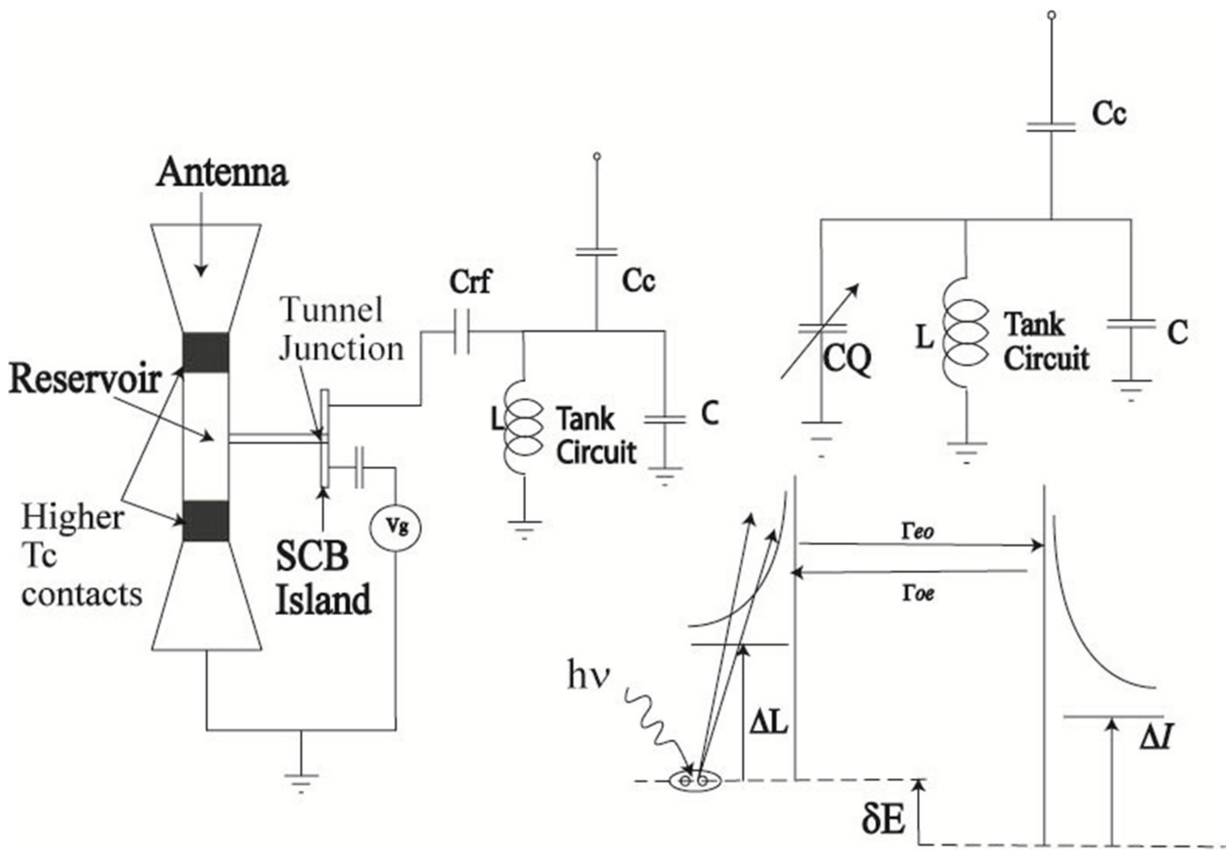
Quasiparticle Poisoning





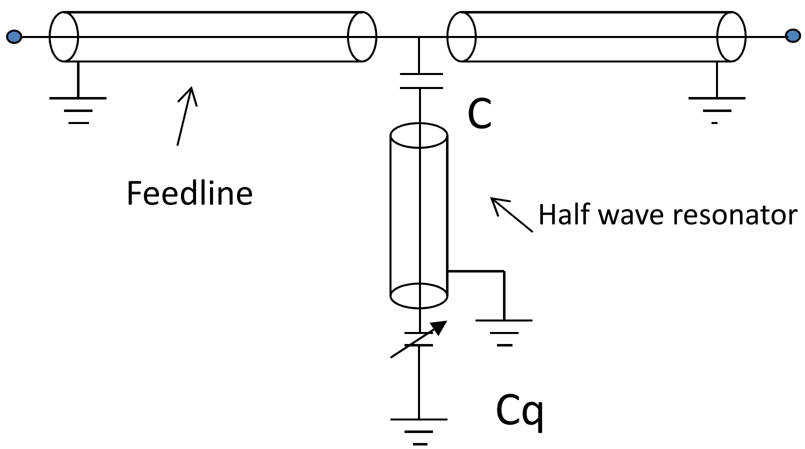
- If there are quasiparticles present in the leads, they could tunnel in and out of the island
- When they tunnel, they shift the effective gate voltage by e/Cg (or ng=0.5)
- Coulomb staircase and quantum capacitance curve shifts by ng=0.5 each time a quasiparticle tunnels in or out.

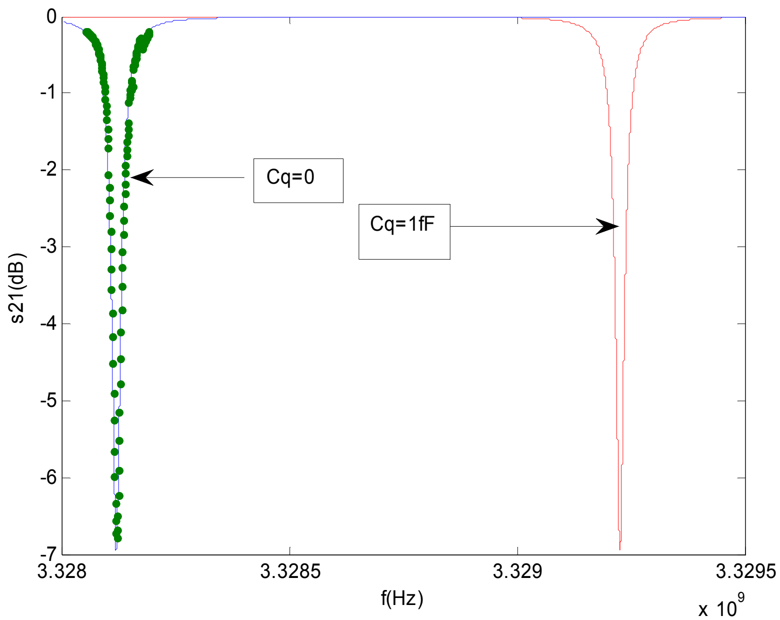
The Quantum Capacitance Detector



- Radiation coupled by an antenna breaks Cooper pairs in the reservoir (absorber)
- Quasiparticles tunnel onto the island with a rate Γ_{in} proportional to the quasiparticle density in the reservoir
- Quasiparticles tunnel out of the island with a rate Γ_{out} independent of the number of quasiparticles in the reservoir
- At steady state the probability of a quasiparticle being present in the island is given by $Po(Nqp)=\Gamma in/(\Gamma in+\Gamma out,)$
- The resulting change in the average capacitance will be $C_Q=(4E_C/E_J)(C_g^2/C_\Sigma)Po(Nqp)$
- *This change in capacitance will produce a phase shift* $\delta\Phi \sim 2C_Q/(\omega_o Z_o C_C^2)$

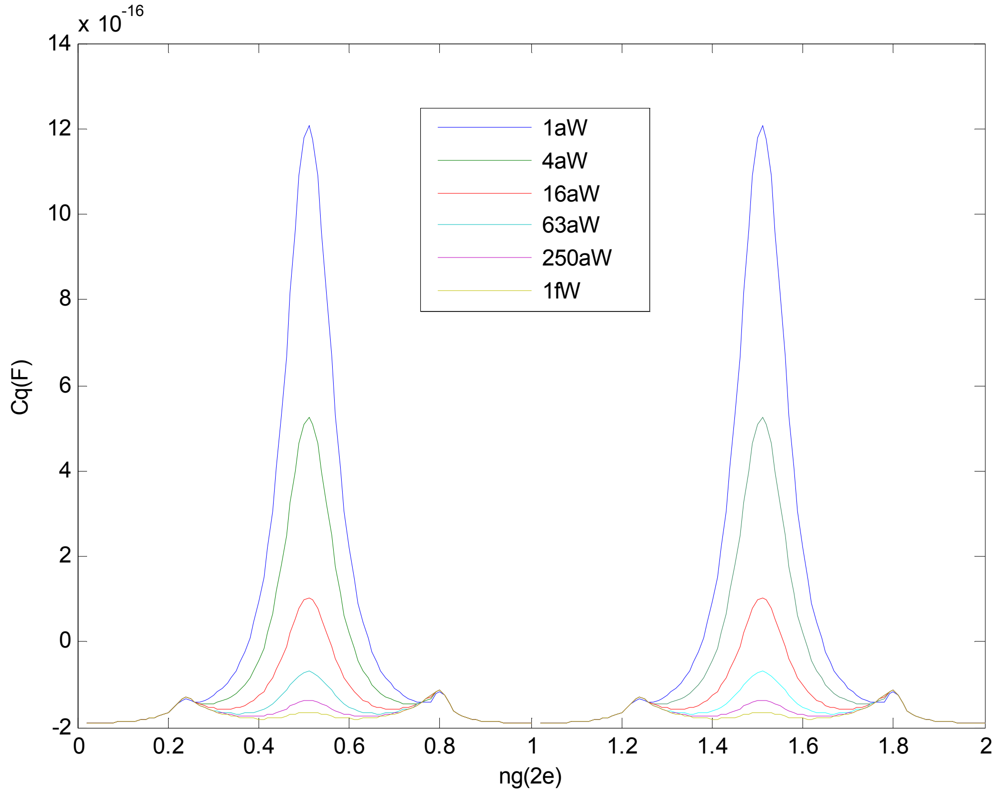
Measurement Technique





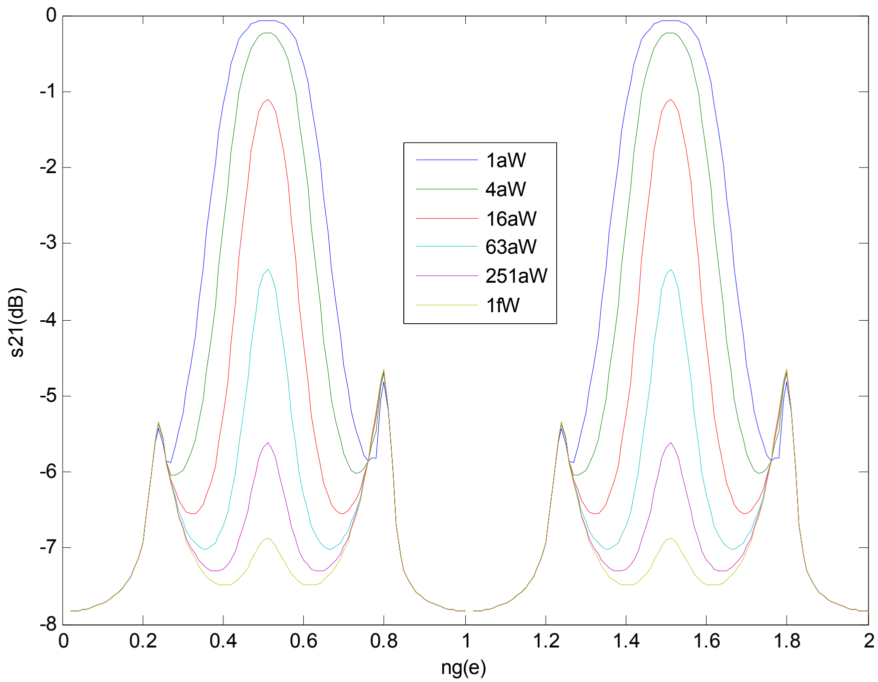
- λ/2 resonator capacitively coupled to a feedline
- SCB is the variable capacitor at the end of resonator
- Change in resonance frequency due to change in quantum capacitance should be large (1MHz)
- Single pixel resonator (green dots)
- Resonance frequency = 3.328118 GHz
- Qi = 220000; Qc= 360000; Qt=136000

Simulated response



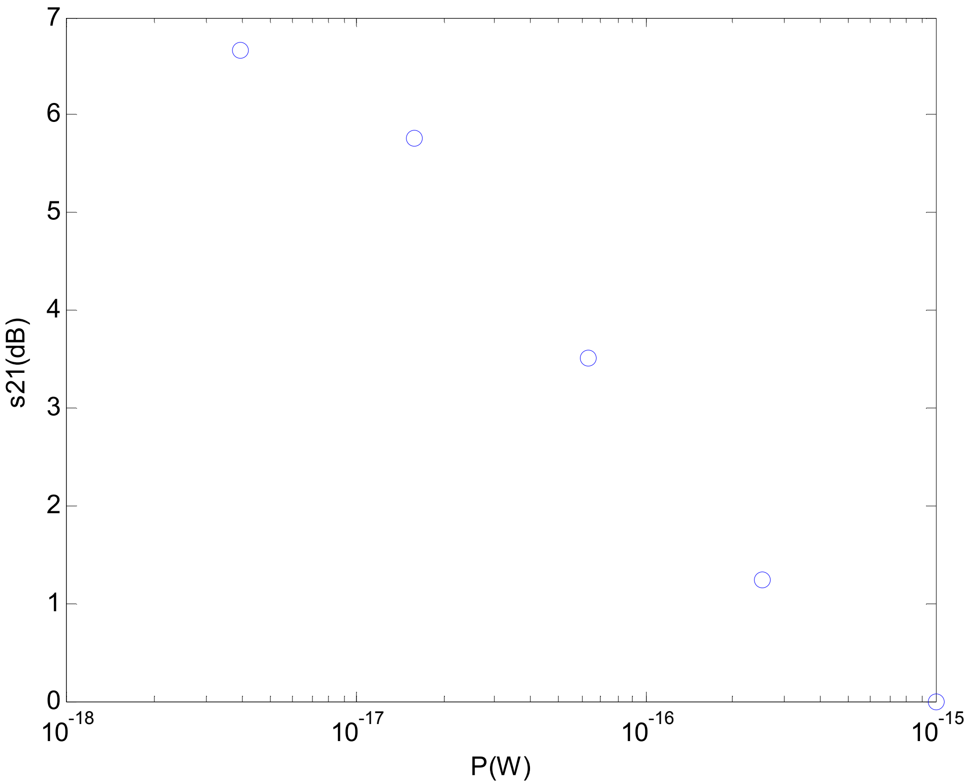
- SCB capacitance x gate voltage (in units of Cooper Pair charge) for different coupled optical signal power

Simulated response



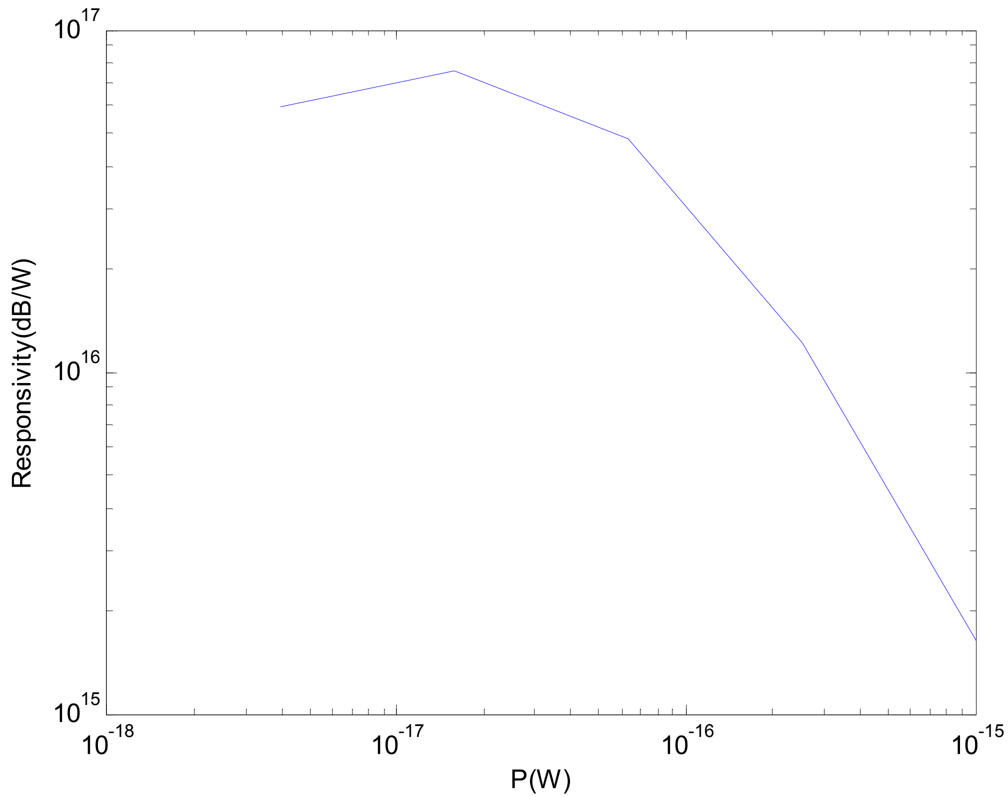
- transmission through feedline x gate voltage (in units of Cooper Pair charge) for different coupled optical signal power

Simulated response



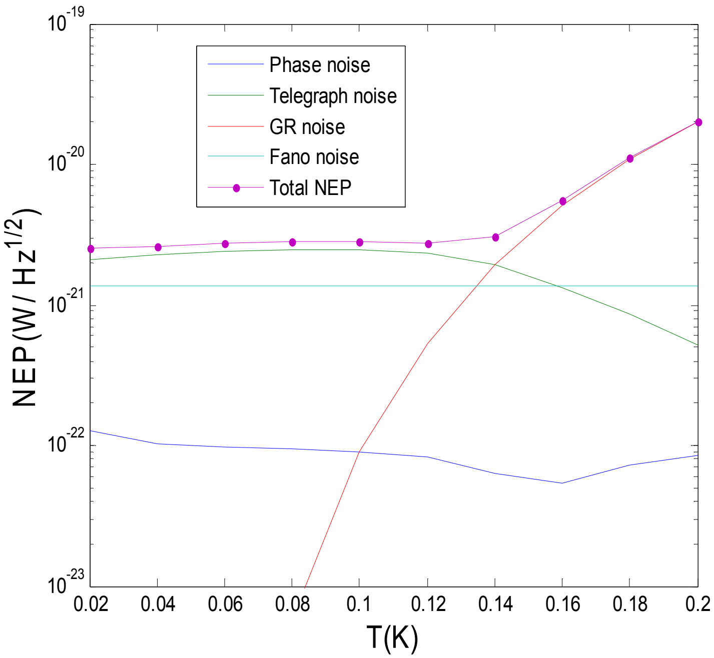
- amplitude of transmission peak as a function of signal power

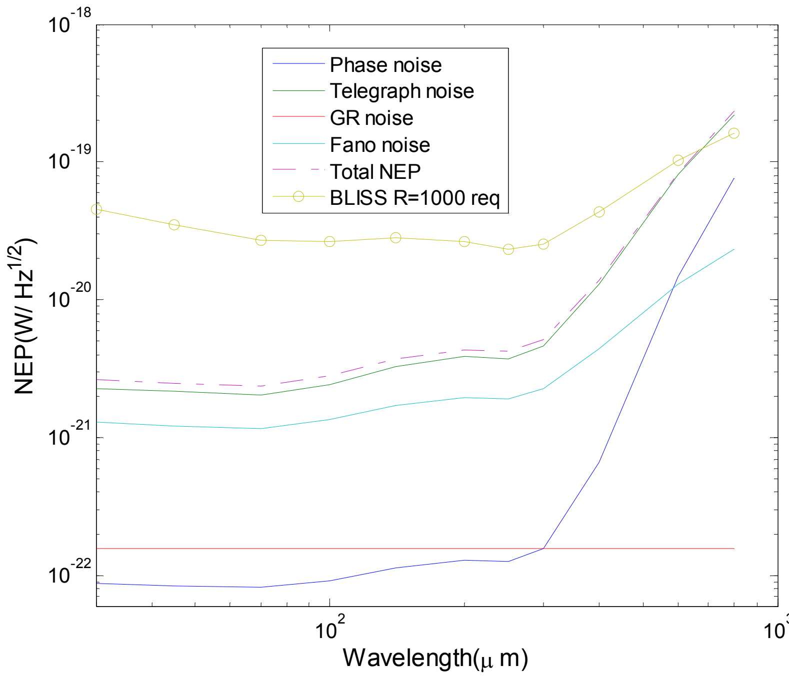
Simulated response



- responsivity as a function of signal power

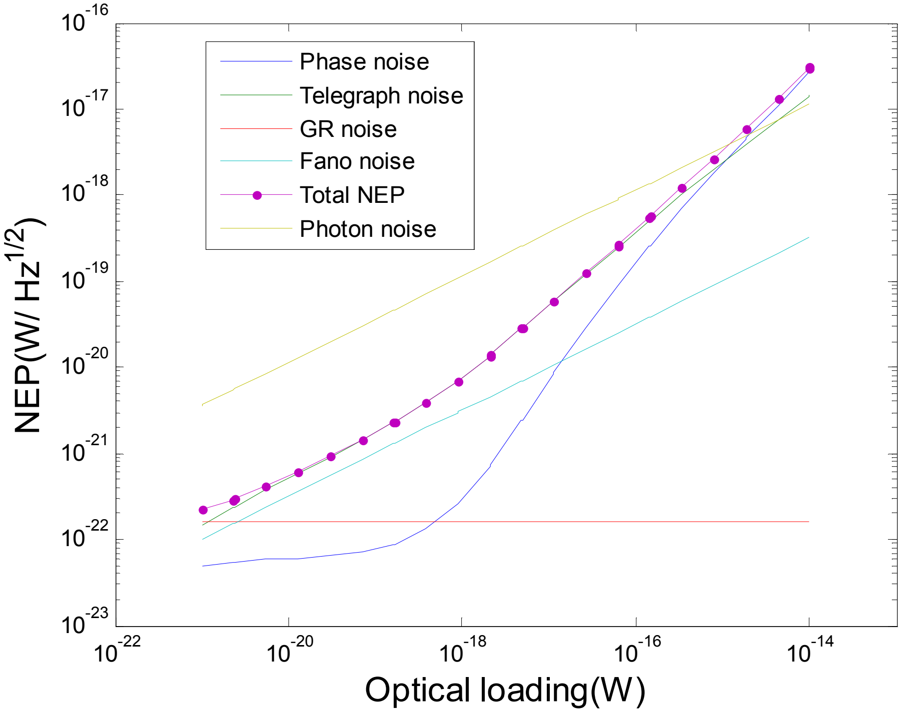
Theoretical Sensitivity





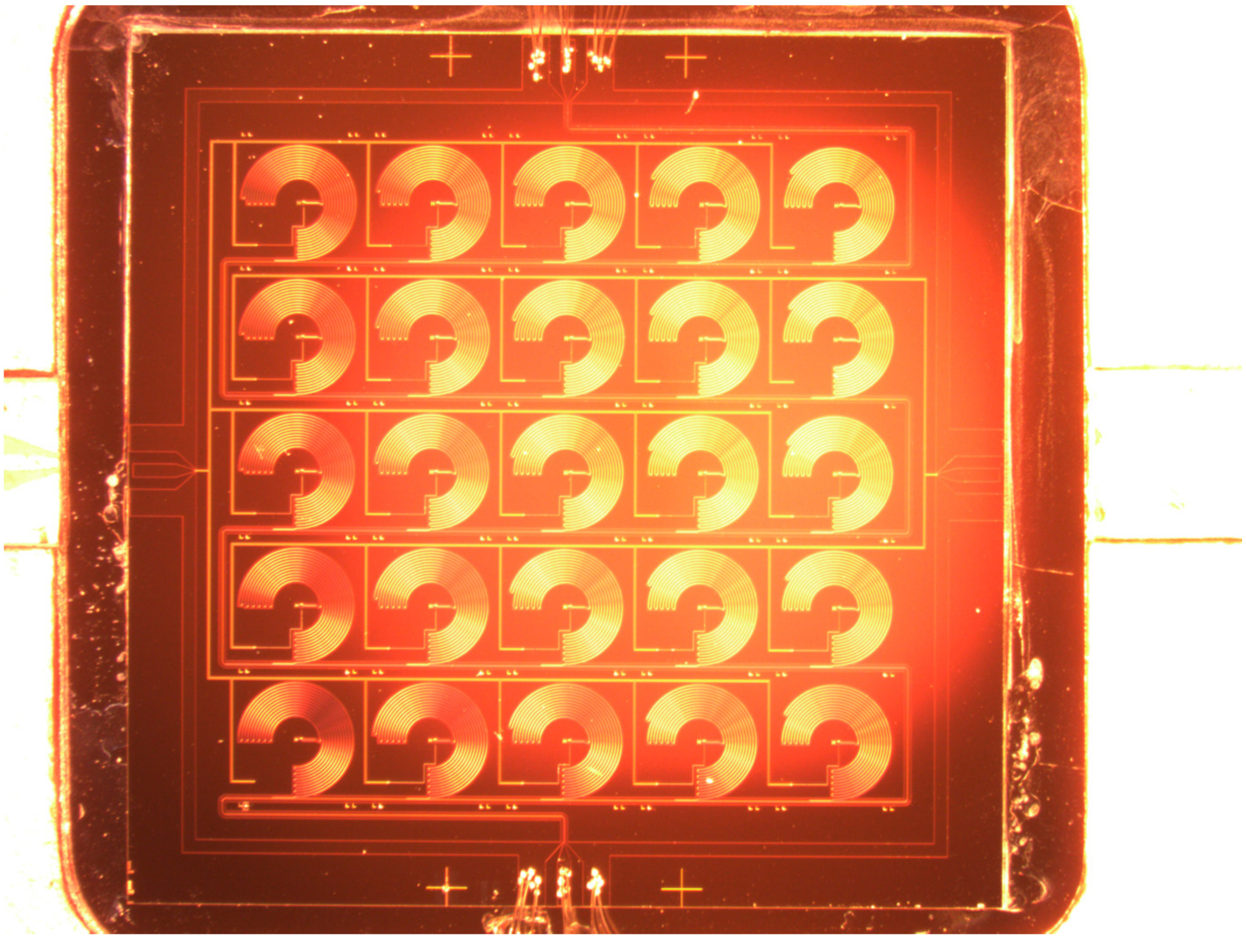
Left: NEPs from various noise sources calculated for devices optimized for λ =100μm, optical loading 10^{-19} W and R=1000 as a function of temperature. Right: NEPs of various noise sources as a function of wavelength as compared to the requirements for a spectrometer with R=1000 and the expected optical loading at L2 for a cold (4.2K) telecope . The operating temperature was chosen to be 0.1K at which the GR noise contribution is negligible.

Theoretical Sensitivity vs. Signal Power

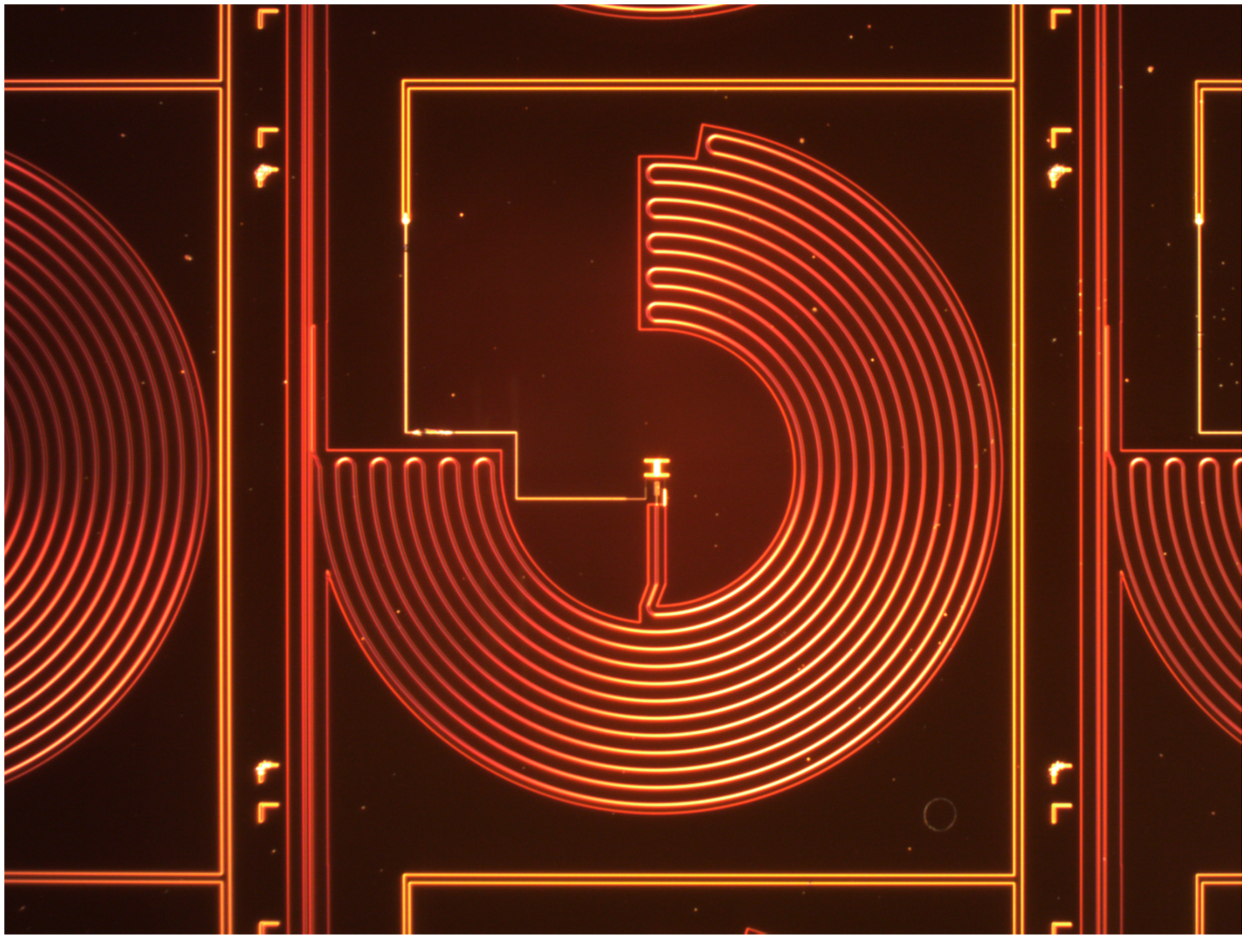


- *Detector is background limited over a wide range of operation*

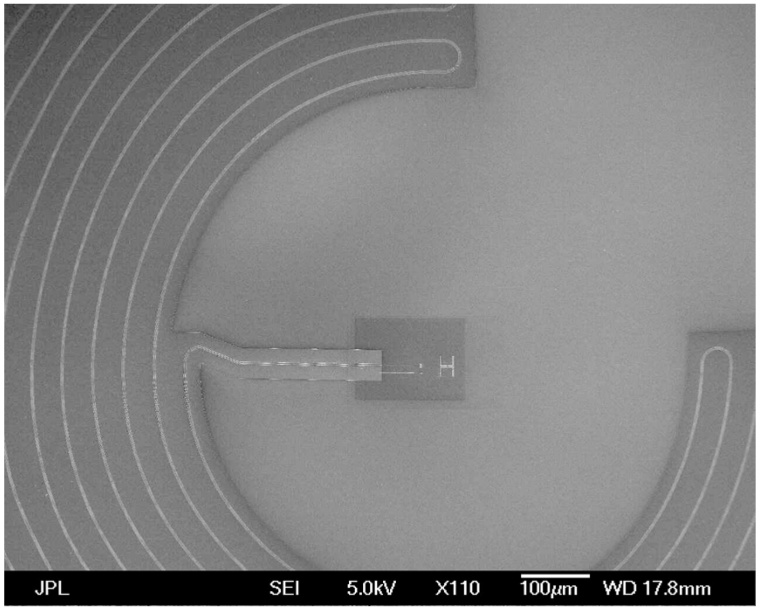
QCD 25 pixel array
Only one pixel illuminated

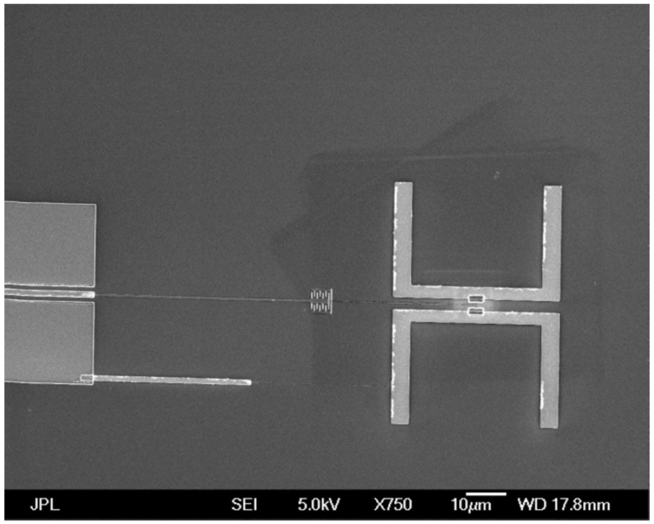


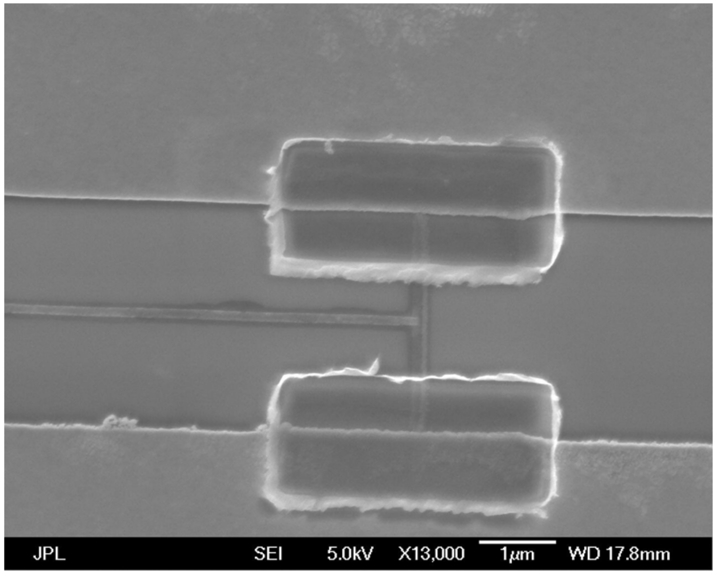
QCD 25 pixel array



SEM pictures







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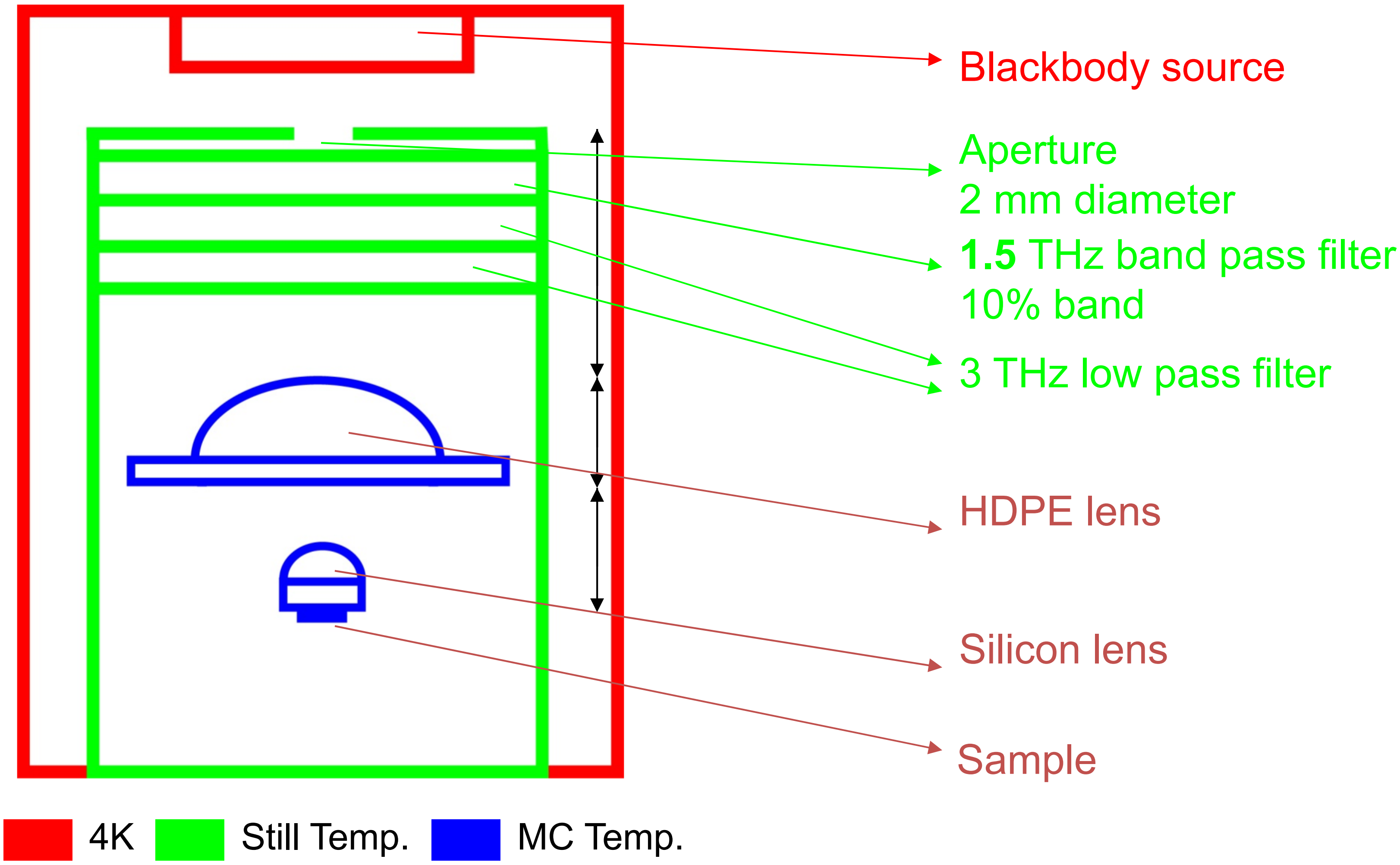
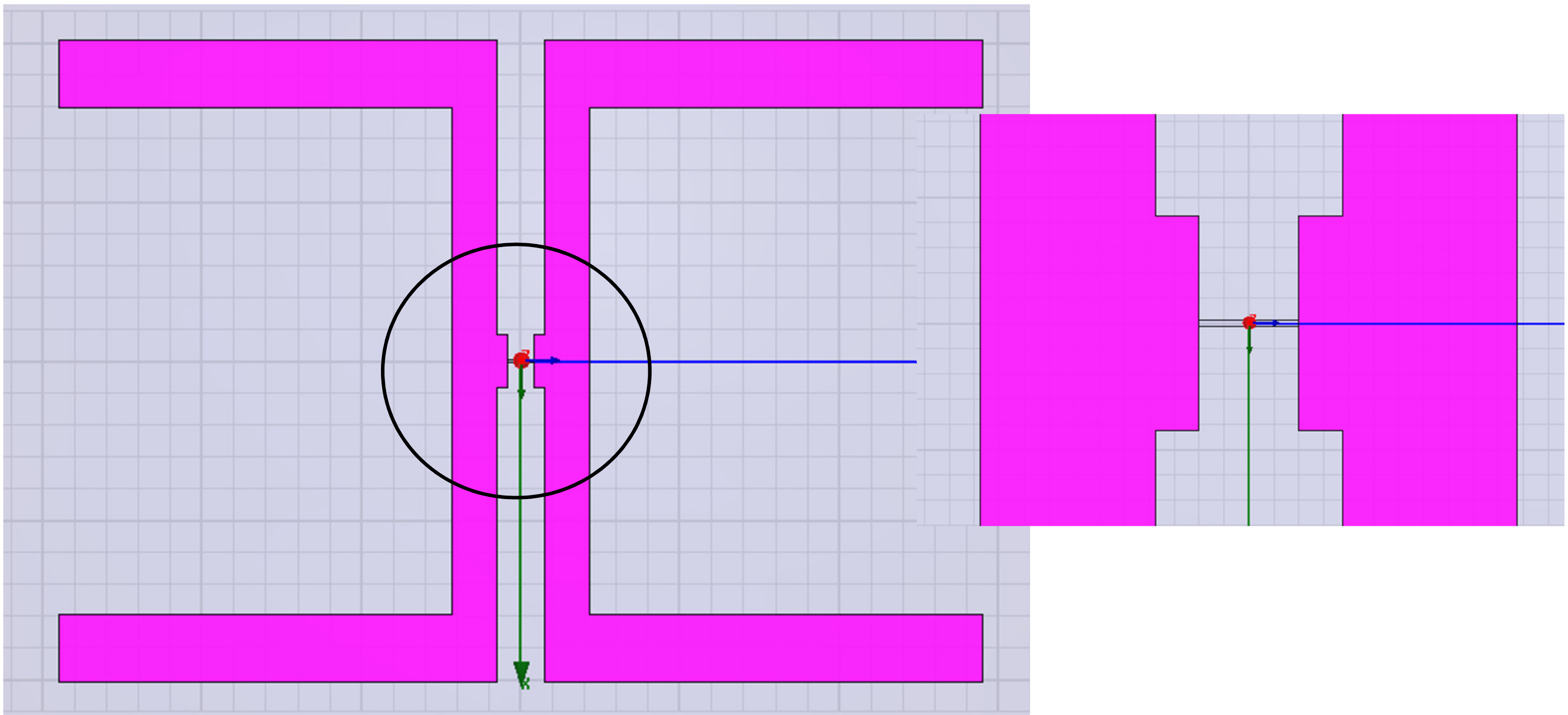
• Nb λ/2 resonator, Au antenna with Al absorber with Nb plug for quasiparticle trapping

• SCB - Al/AlOx/Al

Optical characterization



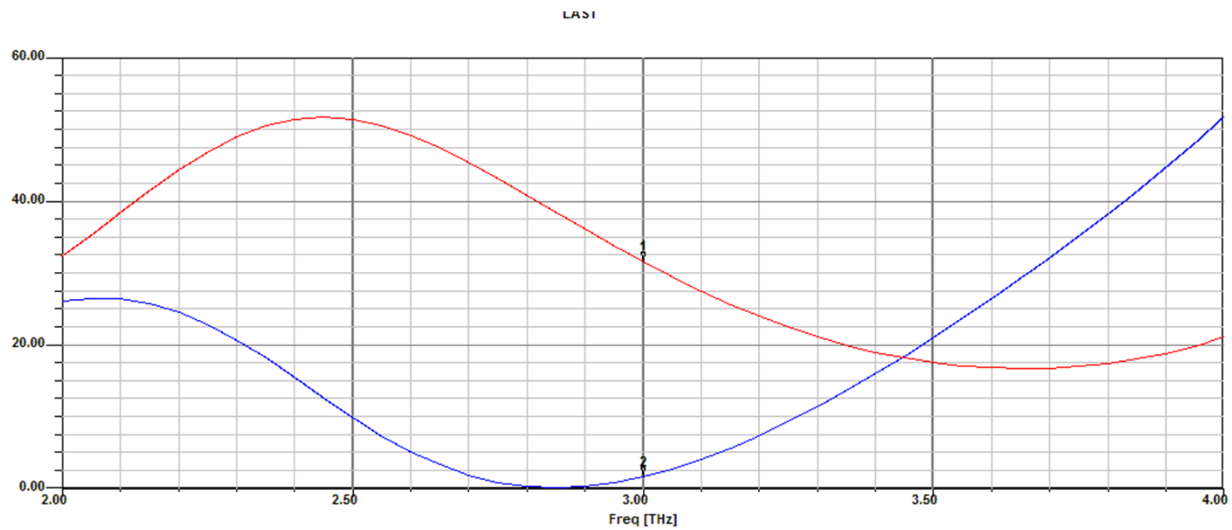
Antenna design

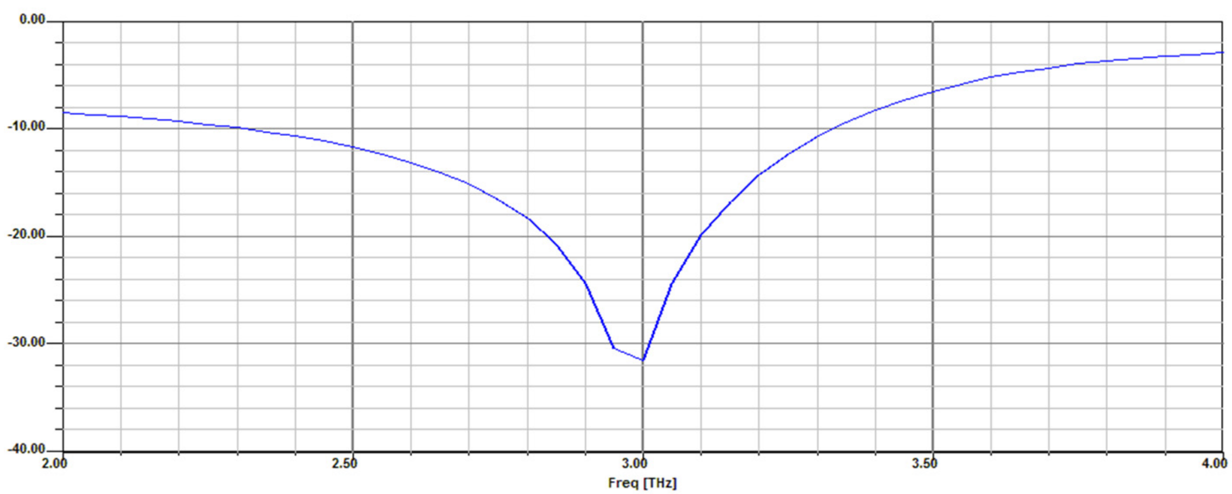


• Double-dipole antenna

• Frequency = 1.5THz   (λ = 200μm)

Antenna design

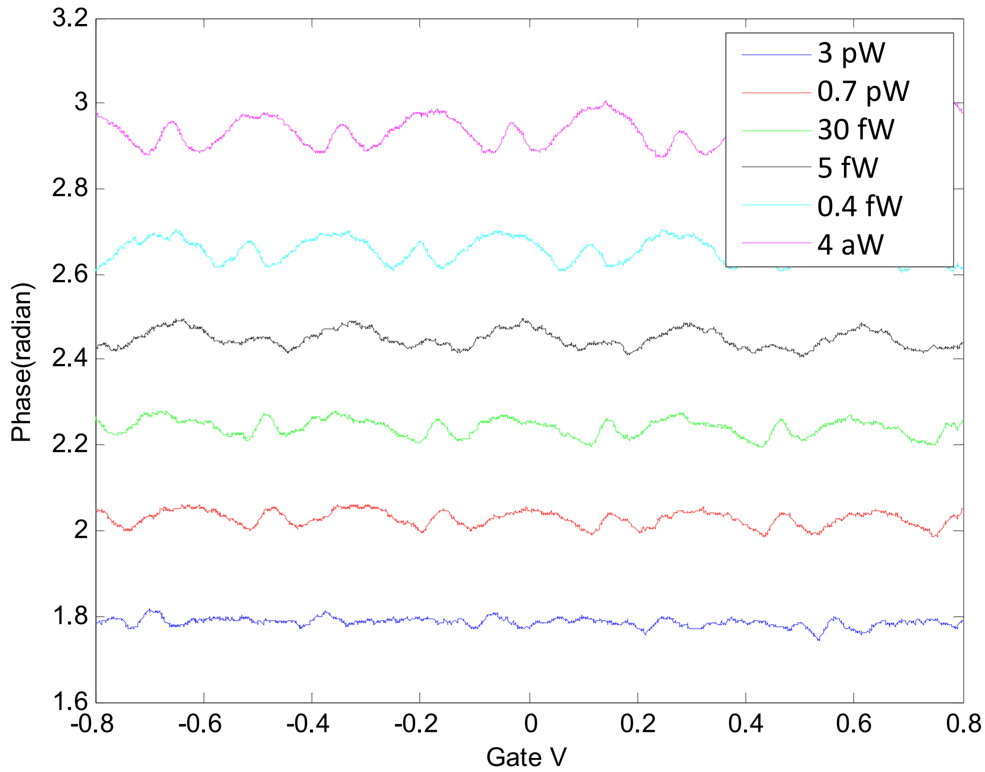




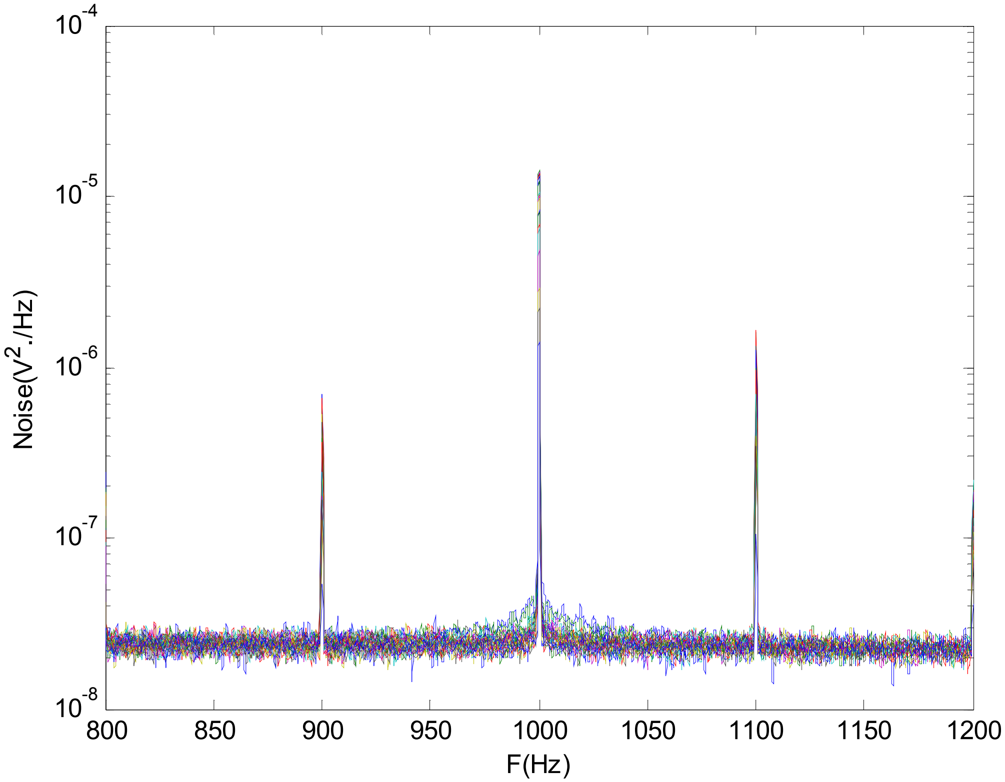
- Z = 32Ω

- Resonance @ 1.5 THz
  - 30% bandwidth

Quantum Capacitance signal x optical power

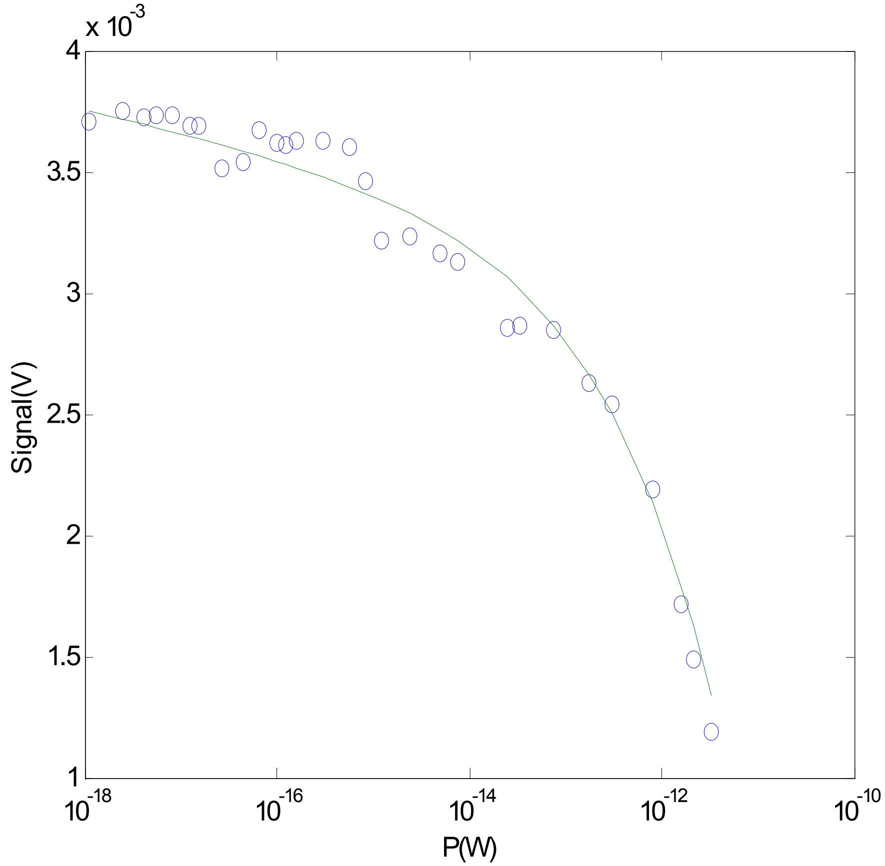


Quadrature signal response



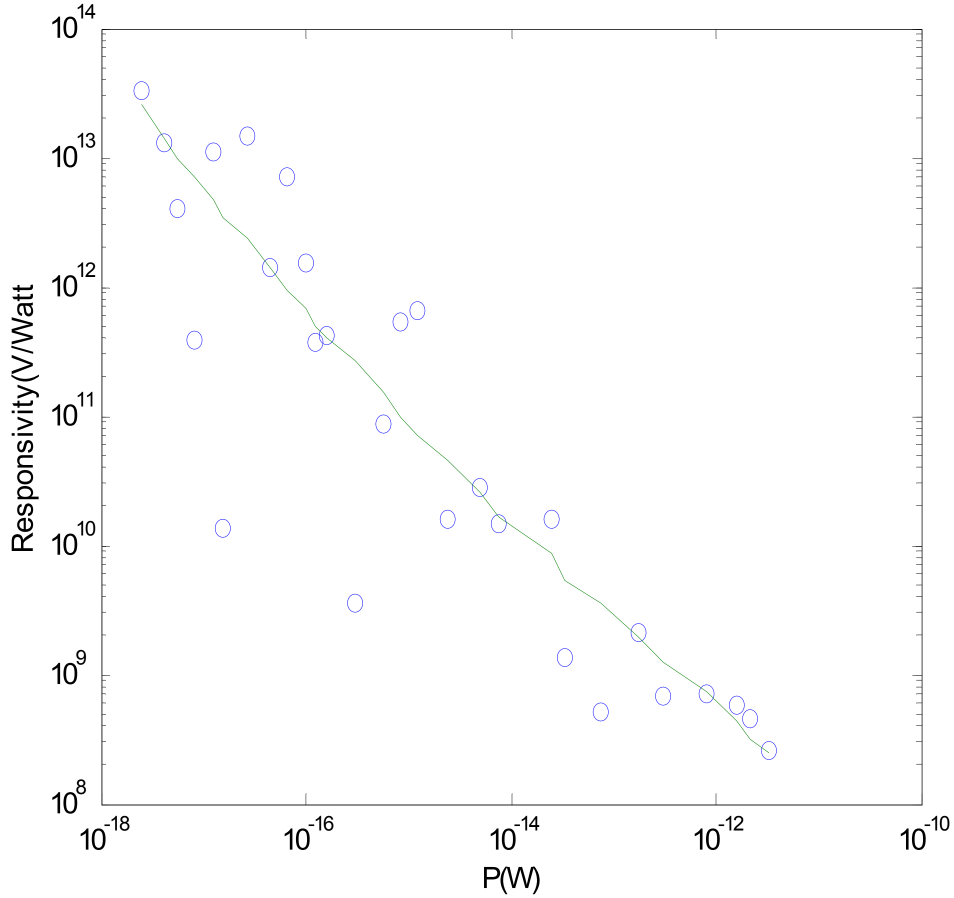
- Applied ramp with amplitude such that 10 peaks were visible
- Ramp frequency 100Hz
- Signal on spectrum analizer had peak at 1kHz
- Measured amplitude of 1kHz peak as a function of black body power

Quadrature signal response



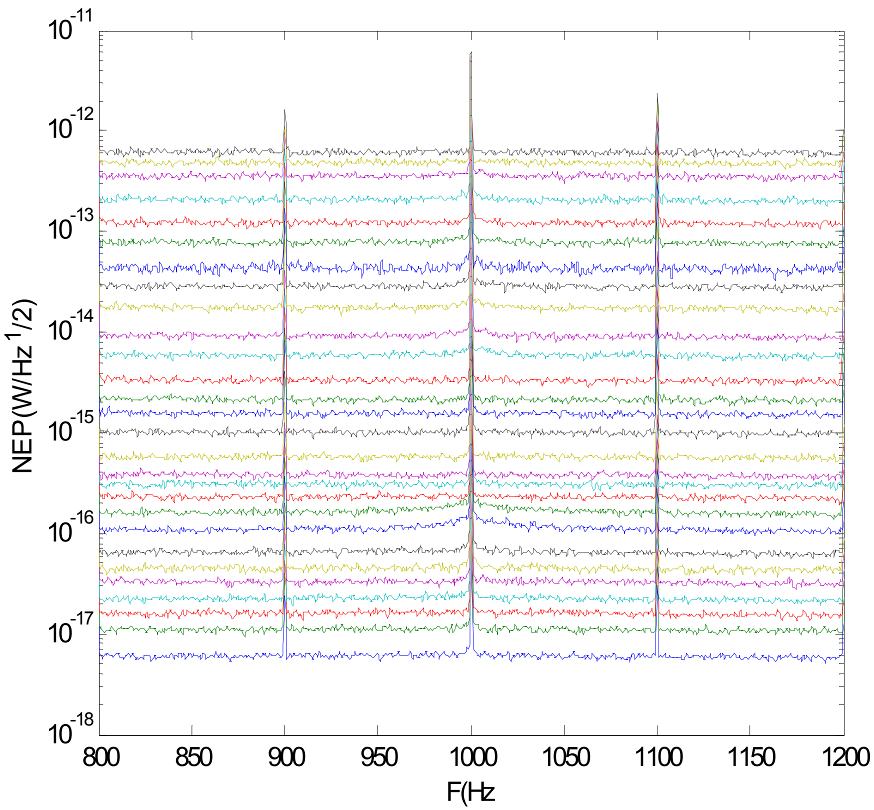
- Plotted amplitude of 1kHz peak as a function f power
- Fit response with empirical formula (green line)

Quadrature signal response



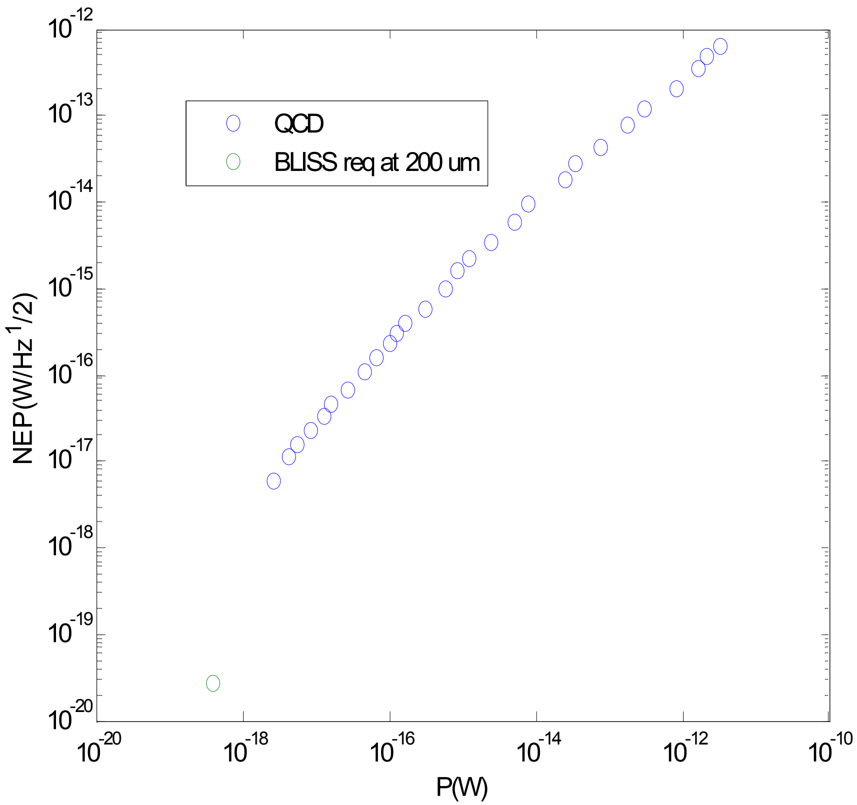
•Calculated responsivity from response fit and from data points

Quadrature signal response



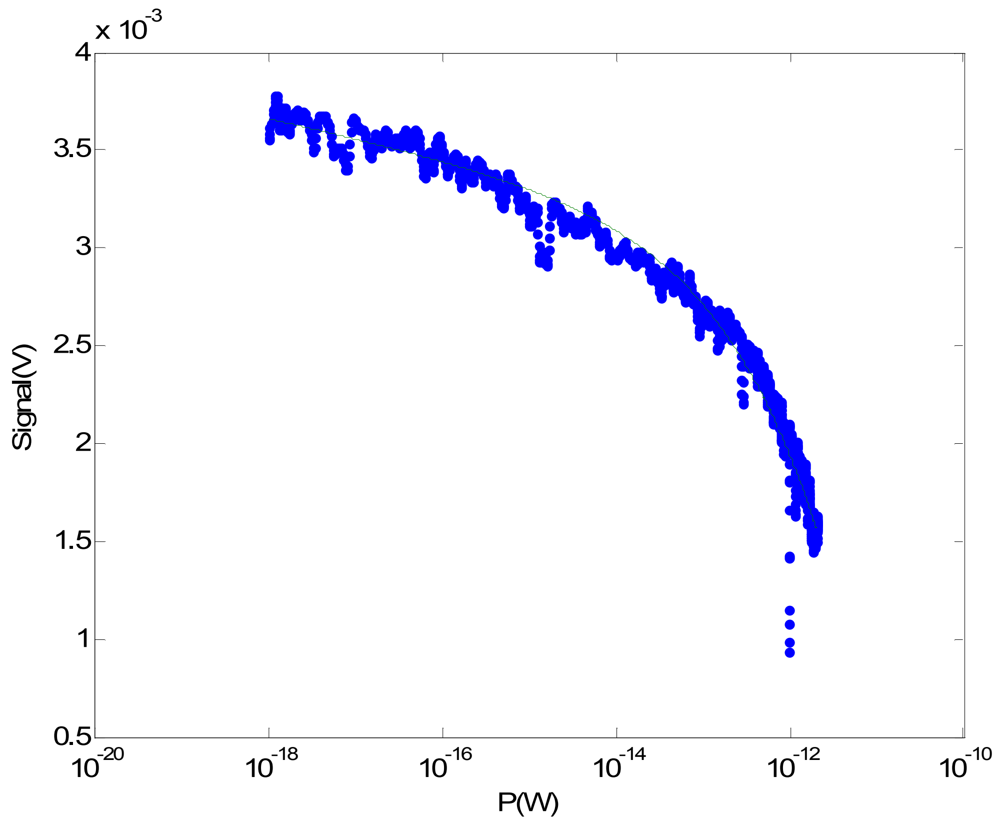
•Calculated NEP from responsivity and noise

NEP x power



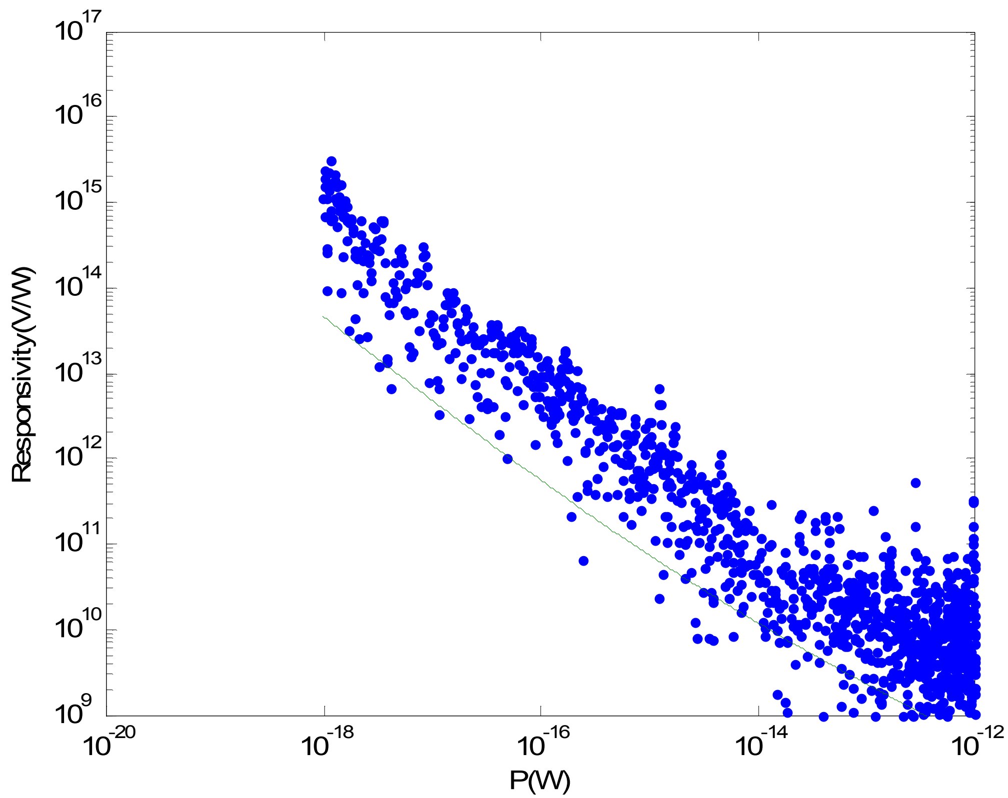
- NEP $6X10^{-18}$ $W/Hz^{1/2}$ at the lowest power $3x10^{-18}W$

Lock-in response – Q signal



- Applied ramp with amplitude such as 10 peaks were visible
- Ramp frequency 100Hz
- Signal on spectrum analizer had peak at 1kHz
- Measured amplitude of 1kHz peak using lock-in amplifier
- Took data passively while cooling and warming black-body
- Fit response with empirical formula (green line)

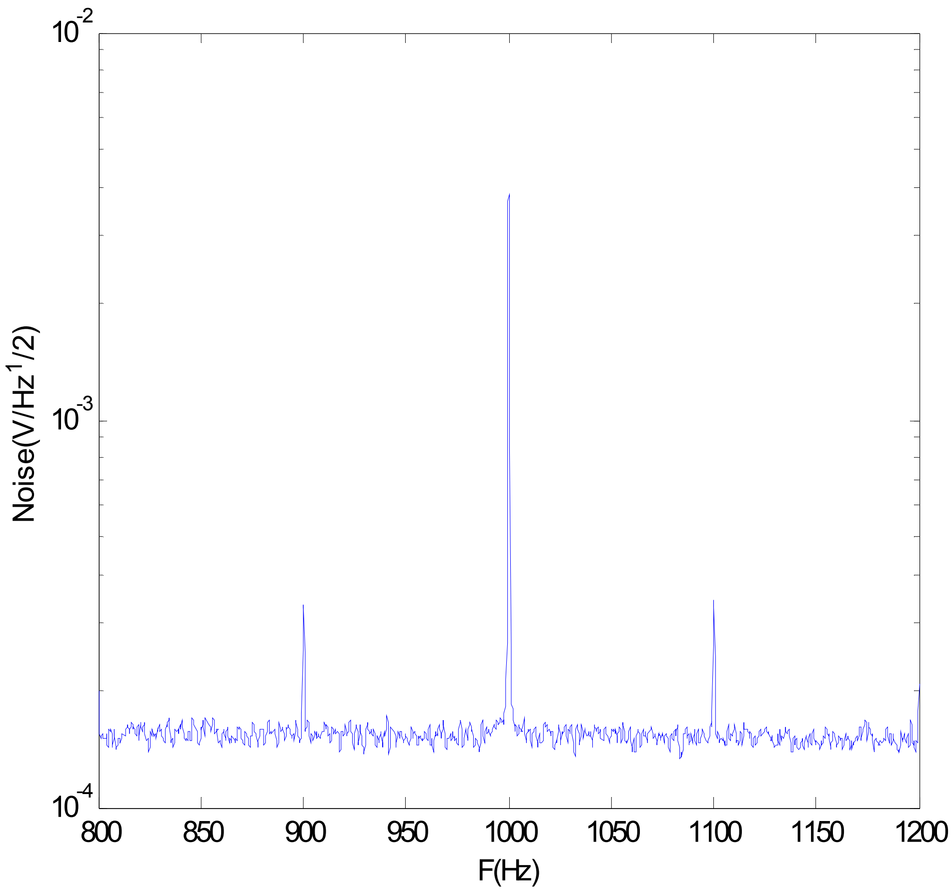
Responsivity (dV/dP)



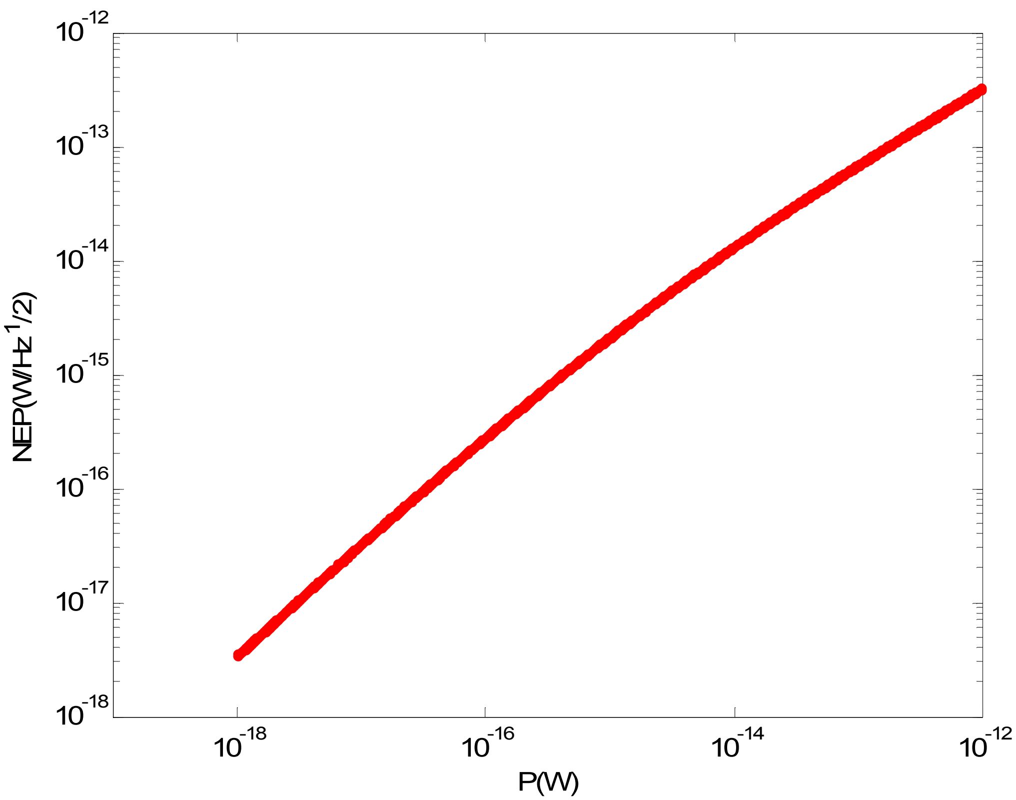
•Took the derivative of fitted response with respect to signal Power(green line)

• Dots are responsivity just taking the derivative of data points

Measured noise and response peak



Noise equivalent power – noise averaged between 920 and 980 Hz



Conclusion

- Achieved NEP $3X10^{-18}$ W/$Hz^{1/2}$ at 1aW
- Actual NEP might be lower, since it depends on the power reaching the device. Any (likely) misalignment would entail a lower power than calculated and hence a lower NEP.
- Resonance peaks should be deeper (as they were in single pixel design)
- Working on resolving this issue
- Should gain an instant factor of 12 when resonance is ideal
- New Si lenses to illuminate 4 pixels
- Working on Fresnel lenses to illuminate all pixels